DEVELOPMENT OF A SELF-POWERED HYDRAULIC SENSING NODE

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DEVELOPMENT OF A SELF-POWERED HYDRAULIC SENSING NODE

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SUMMARY

In modern industrial settings, a significant amount of energy is wasted in the form of sound, physical vibrations, and pressure variations in gases and liquids. Given the recent advances in low power processing and communication devices, there is now an opportunity to capture this energy and use it to power sensing and communication components. A device that is able to power itself using ambient energy would be an innovative replacement to wired or battery-powered sensors which can be costly and difficult to maintain. Past efforts in this area have been stymied by the low energy densities that are present in ambient sources such as light and vibrations, but pressure fluctuations in hydraulic systems offer a much denser energy source. Previous work developing a piezoelectric energy harvesting device has generated 2.6mW of power from a hydraulic test rig operating at a static pressure of 5.5 MPa with a 9-piston pump operating at 1500 RPM. This Hydraulic Pressure Energy Harvester (HPEH) device has the potential to generate power which could be used for remote sensing and communication purposes in a variety of hydraulic systems. This paper presents an implementation of a HPEH device connected to a communications system that allows it to store energy and communicate sensor readings via Bluetooth Low Energy. The levels of power that are produced by the energy harvester and consumed by the communication components are analyzed, with special attention paid to the power consumption of a connected microcontroller during different operations. Additionally, an evaluation of the wireless data transmission rates that can be supported by the power output of a HPEH device is included.

CHAPTER 1

INTRODUCTION

The recent push to maximize efficiency and productivity in industrial settings has led to increased attention being paid to the operating conditions of manufacturing plants and equipment. As a result, the market for lower-power industrial sensors has been growing rapidly [1]. Most industrial sensors today are powered through a wired connection or batteries, which can make these sensing systems susceptible to failure and costly to maintain. If a sensing network could be self-powered, though, it would be more robust than a series of wired sensors while producing less waste than battery-powered sensors. This opportunity has motivated a great deal of research into harvesting energy from ambient sources.

Acoustic disturbances such as sound waves represent one possible source of ambient energy. Energy harvesters developed for these sources often use piezoelectric material to convert the acoustic energy into electrical energy [2, 3, 4]. To maximize the power that can be recovered from common acoustic sources, researchers have utilized Helmholtz Resonators [2] and sonic crystals [4]. However, no concentration or amplification device is able to reconcile the problem that airborne noise has a relatively low energy density when compared to the power needed for sensing and communication processes. While energy harvesting experiments by Taylor et al. have yielded power levels between 20 and 30 milliwatts, they were conducted within turbofan engine nacelles, where noise levels can exceed 150 dB [5]. As the level of a sound wave decreases, so does the power intensity of that wave. For comparison, 100 dB noise, both hazardous to humans and uncommon in industrial setting, carries a maximum intensity of 0.001 mW/cm^2, meaning that an energy harvester capable of producing usable levels of power would need to be unfeasibly large [6]. These difficulties suggest that it could be worthwhile to look elsewhere for viable sources of ambient energy.

Hydraulic pressure ripple presents an appealing source for energy harvesting because of its high energy density and narrow frequency content. Industrial hydraulic systems operate at pressures up to 35 MPa and the pumps that drive the hydraulic fluid induce changes in pressure that can reach 10% of the static pressure. These high static pressures and the high density of hydraulic fluid creates waves with much larger intensities. An energy harvesting device that could capture a significant portion of this power would be able to support a variety of low power electronics performing sensing and communication functions. Previous work has been done to create such a device and testing on versions of a Hydraulic Pressure Energy Harvester (HPEH) has yielded 2.6 mW of power when exposed to a hydraulic system operating at 5.5 MPa [6].

The power produced by a HPEH device is adequate to power the necessary components of a self-powered sensing node. The sensing system presented here was designed to use the power produced by a HPEH device to sample operating conditions of the hydraulic system such as its temperature, pressure, or flow rate. This report will detail the proof-of-concept sensing system that has been developed, which includes an energy harvester, power conditioning circuit, and a low-power microcontroller with Bluetooth Low Energy (BLE) functionality. The average power consumption of the sensing node will be analyzed at various sampling rates to determine the kinds of sensing applications that this system could be applied to.

Power consumption by the sensing system can be attributed to a few different functions, including sensor sampling, data processing (e.g., integration of samples into a single "packet"), and wireless transmission. These functions will be identified and compared in the context of a power consumption timeline taken over a full transmission cycle. By identifying the energy consumption of wireless transmission and sensor sampling, operators can customize the sampling and communication schedule of a sensing node to the amount of available energy. If this analysis is performed well enough, one can imagine that a network of these sensing nodes could be employed across a hydraulic system to fully monitor the hydraulic fluid and system without requiring maintenance work or component replacement.

CHAPTER 2

LITERATURE REVIEW

In many industrial operations, a sizeable portion of the energy that is generated is lost to vibration, heat, or sound. Many recent studies have shown that it is possible to develop harvesting systems to capture and store this previously wasted energy. Often, piezoelectric material is embedded within these systems because it produces electric current when subjected to changing stress. One application for ambient energy harvesting is provide power to a network of sensing and wireless communication devices. If self-powered sensing could be implemented, it would remove the need for wired power connections and batteries, both of which can be unreliable and costly. Such a use case, though, would require continuous power on the scale of milliwatts. Existing literature contains information about the power that different ambient energy sources can provide as well as techniques to amplify the amount of energy that can be captured. Up to this point, fluidic and airborne acoustic energy sources have been the focus of most energy harvesting research. However, a system that provides high levels of power reliably from these sources has yet to be put forth.

Fluids, both liquid and gaseous, present a potential source for energy harvesting. Previous studies have attempted to capture a portion of the kinetic energy of a moving fluid by placing an obstacle in the path of the flow to induce turbulence in the fluid. A piezoelectric material that is placed in this area of turbulence will deform and produce an electric current that can be used to charge a battery [7,8,9]. Allen and Smits [9] explored this method of harvesting energy by positioning a piezoelectric "eel" behind a bluff body meant to disrupt the flow of water within a piping system. Their research demonstrated that this type of system was capable of producing a voltage source but was primarily concerned with analyzing the vibratory response of the piezoelectric material. Pobering and Schwesinger [7] expanded upon this work by designed and testing a vibrating piezoelectric harvester in the path of both air and fluid flow. Another method for converting a fluid's kinetic energy into electrical energy is to position a piezoelectric cantilever beam in the path of a moving fluid. As a gas or liquid passes over the cantilever beam, it will begin to oscillate, creating material stress upon a piezoelectric film mounted to the surface of the beam [8]. An important downside of energy harvesters that use fluid flow as an energy source is that they must somehow disrupt the system in which they are embedded. A harvesting device that could be installed on the periphery of an energy source would be easier to maintain and less prone to failure.

Airborne sound presents a source of energy that often goes to waste and would allow a harvesting system to produce power without making a significant impact on surrounding processes. Several studies have demonstrated the feasibility of such a design and most use piezoelectric material as the means of generating electrical energy [2,3,4,5,10]. An early implementation of this technology was presented by Horowitz et al. [2] in the form of a piezoelectric ring embedded in a circular diaphragm. As this diaphragm vibrates in response to incident acoustic energy, the piezoelectric material creates a current used to charge a nearby battery. Taylor et al. [5] took this application a step further by identifying an industrial energy source and use for the harvested energy. Acoustic liners are often installed within engine nacelles to suppress noise and powered liners are able to lower sound levels more effectively by reacting to different operating conditions. The research team was able to develop a self-powered acoustic liner that can be tuned to match incoming noise while also generating power that allows it to communicate wirelessly. While airborne energy sources are appealing because they are prevalent in industrial settings and easy to access, the amount of energy present within sound often does not justify harvesting it.

Realizing this problem, several attempts have been made to enhance energy harvesters and increase the amount of power that they can collect. Matsuda et al. [3]

argues that a cone-shaped Helmholtz Resonator can be used to this effect. When this device was incorporated into their airborne energy harvesting system, the amount of power that was generated increased by a factor of 8.6. A similar attempt at amplification was made by Wu et al. [4] by embedding their acoustic energy harvesting system within a sonic crystal. Sonic crystals, collections of regularly spaced obstacles, create concentrated areas of vibration in a particular region. In this environment, Wu's acoustic energy harvesting system was able to gather 25 times more power compared to a system that had no sonic crystal present.

While these amplification devices have been successful in increasing the amount of energy that can be produced from ambient sources, these enhanced levels of power can still pale in comparison to the amount needed to operate basic sensing and communication equipment. Microcontrollers capable of sensing and wireless communication require power on the order of 10^{-3} Watts [6]. In contrast, the acoustic energy harvester designed by Wu et al. [4] produced 1.4×10^{-13} Watts after the addition of the Helmholtz Resonator. This production rate has been improved by Horowitz et al. [2] whose airborne energy harvester showed a power generation rate of 0.34×10^{-6} Watts/cm^2. However, this higher rate still means that a harvester capable of outputting 1mW of power would need to have an area of 294m^2. Fluidic energy harvesters have also not demonstrated the ability to produce sufficient power for a wireless sensing device. Pobering and Schwesinger's [7] study of power production from air flow produced 0.1×10^{-3} Watts during wind tests at 45m/s while St. Clair et al's [8] cantilever-based design generated a maximum power level of 0.8×10^{-3} Watts. Taylor et al. [5] successfully tested an acoustic harvester capable of outputting up to 30×10^{-3} Watts of power but this was when their energy harvester was subjected to noise levels of 151dB, a magnitude that is well above the limit of sound that is hazardous to human hearing [6]. These disadvantages may be avoided, however, by looking towards hydraulic pressure ripple as a potential source for energy harvesting.

High pressure hydraulic systems often operate at pressures around 35MPa, several orders of magnitude greater than atmospheric pressure. Pumps driving this fluid through hydraulic pipes operate at a consistent frequency and can create slight changes in the pressure of the system, often 5-10% of static pressure [11]. These pressure fluctuations can have significantly higher energy densities than airborne vibrations or fluid flow, making them an appealing source for a new type of energy harvesting system [6]. The study discussed here will evaluate the power generation of a hydraulic powered energy harvesting (HPEH) device, to analyze whether hydraulic acoustics can provide adequate power for sensing and communication equipment. If the amount of energy generated from this device can reliably power a microcontroller sending sensor readings over Bluetooth Low Energy, this will set hydraulic pressure fluctuations apart from previous energy harvesting sources. As a source of power that has higher energy density than any previously studied source and is common across many industrial and manufacturing settings, hydraulic systems could present an opportunity to implement a self-powered sensing and communication system.

CHAPTER 3

METHODS AND MATERIALS

A proof of concept for a self-powered sensing node has been developed, functionally depicted in Figure 1. Electrical energy originates within the power conditioning and storage system and is then transferred to the data acquisition and communication system. Sensor data is generated within this system and then sent over a Bluetooth Low Energy (BLE) signal to the central base station. Within the central base station, the BLE signal is received, processed, and stored on a data collection device. The following sections provide greater detail on each of these functional elements.

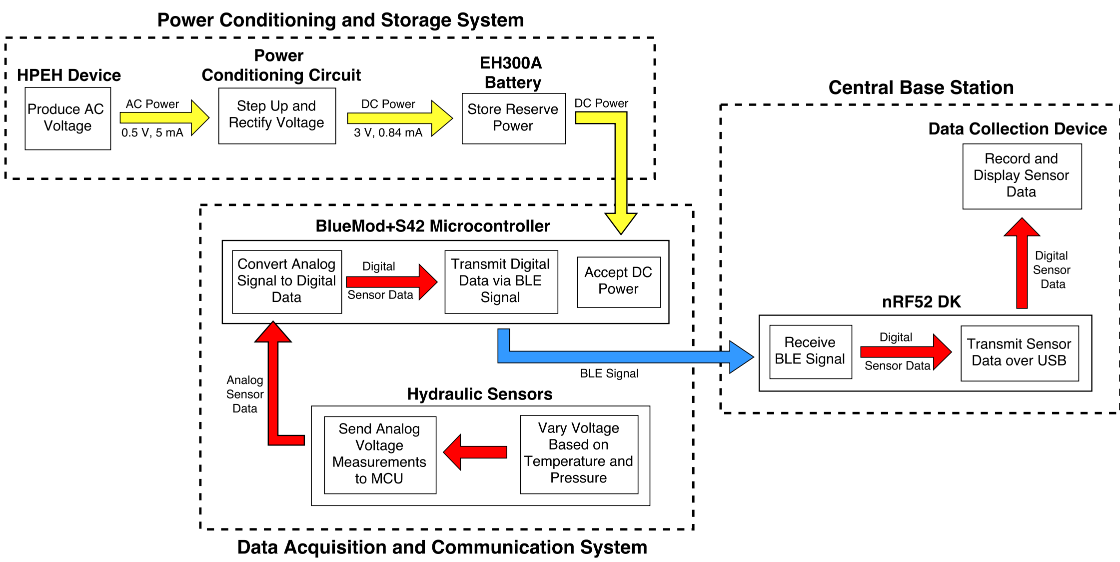

Figure 1: Sensing Node Functional Diagram

A. Power Conditioning and Storage System

The power conditioning and storage system is composed of three components which can be seen in Figure 3: a HPEH device, power conditioning circuit, and a battery. The HPEH device is responsible for converting the ambient energy present within hydraulic pressure ripple into electrical energy. It is composed of a metal housing which can be screwed into a hydraulic mounting port to expose it to the hydraulic fluid. Present within the HPEH is a piezoelectric stack which is separated from the hydraulic fluid by a stainless-steel diaphragm. This diaphragm acts as a seal between the hydraulic fluid and energy harvesting system while allowing stress upon the piezoelectric stack to vary based on the fluid pressure. The cyclical nature of dynamic pressure ripple within a hydraulic system causes the HPEH device to output an AC voltage with a magnitude on the order of 100's of millivolts. This power must be conditioned and stored to make it suitable for input to the data acquisition and communication system.

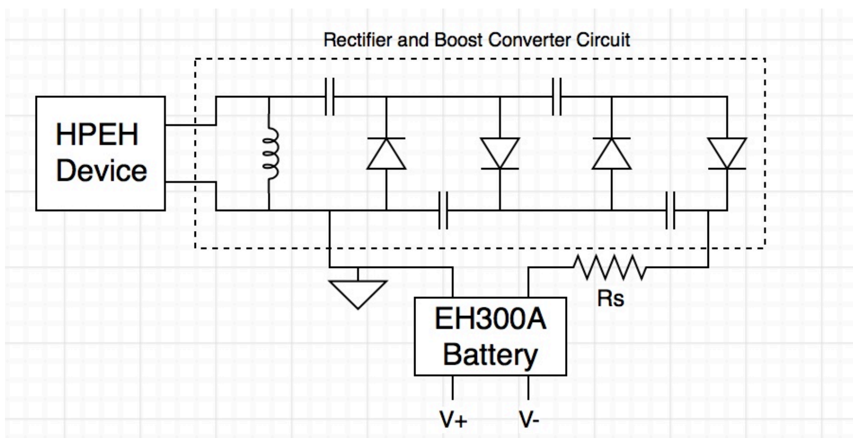

Figure 2: Power Conditioning Circuit Schematic [12]

An EH300A energy harvesting battery acts as an energy reserve within the power conditioning system. As the acquisition and communication components progress through the transmission cycle, they will draw varying amounts of power, sometimes requiring more than the steady state power ouput of the HPEH device. The battery is required to store energy coming from the HPEH device during periods of low power consumption in order to provide increased levels of power during periods of higher consumption. This ensures that as long as the average power consumption of the data acquisition system is less than the steady state output of the HPEH device, the sensing node will operate continuously. Because the EH300A battery requires input power with a voltage greater than 3V, a power conditioning circuit is needed between the HPEH device and the battery.

This circuit, shown as a schematic in Figure 2, acts as a boost converter and rectifier for the power harvested by the HPEH device [12].

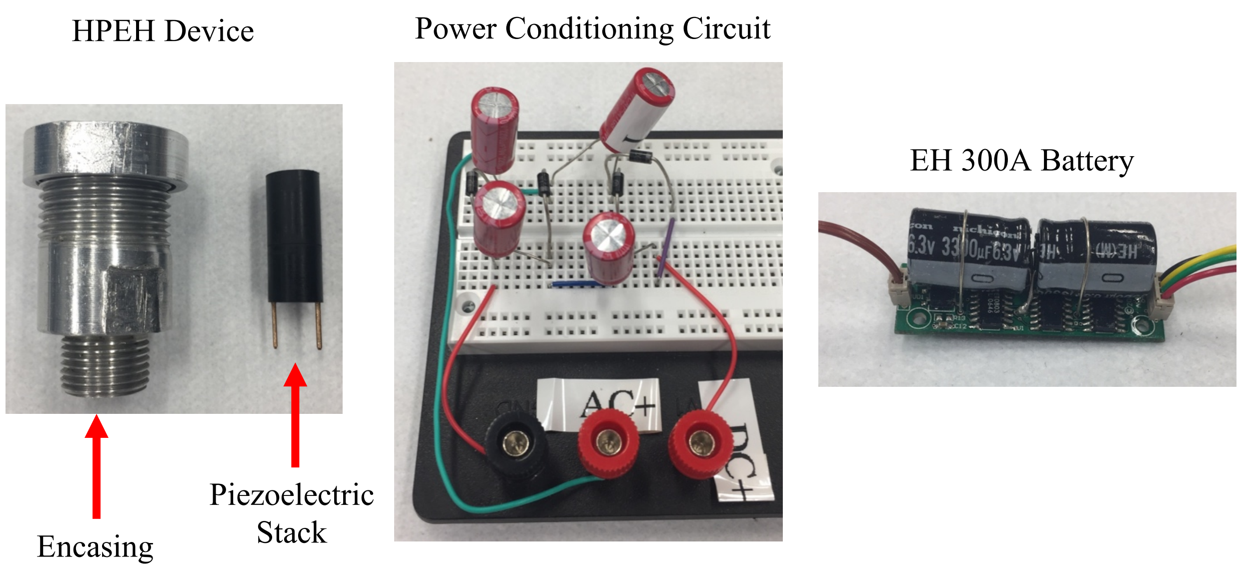

Figure 3: Power Conditioning and Storage Components

Input power to this circuit is converted from an AC signal with a voltage on the order 100’s of millivolt to a DC signal with a voltage above 3 Volts. This power can then be stored in the battery and consumed by the data acquisition and communication system as needed.

B. Data Acquisition and Communication System

The intended use for the power harvested by the HPEH device is to periodically sample the operating conditions of the hydraulic fluid and transmit this data over a wireless connection with a central base station. The components responsible for these functions exist within the data acquisition and communication system, which includes a BlueMod+S42 microcontroller, shown in Figure 4, and any hydraulic sensors that are being sampled.

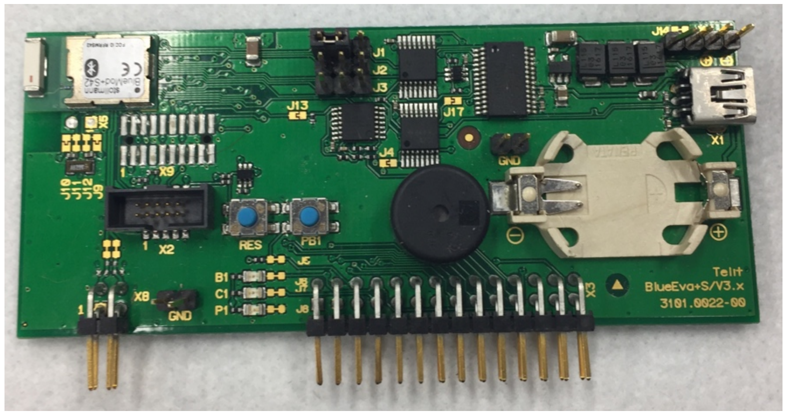

Figure 4: BlueMod+S42 Microcontroller

Telit's BlueMod+S42 microcontroller is designed to consume as little power as possible while maintaining a wireless BLE connection. The required current levels, with a source voltage of about 3V, corresponds to power consumption on the order of milliwatts which is feasible for a HPEH device to supply. The Bluetooth Low Energy wireless protocol stood out as being optimal for low-power communication over moderate distances. So, a microcontroller that could transmit over this standard was chosen. Sensor measurements can be gathered by sampling one or more of the BlueMod's analog input pins pins and converting these readings using the BlueMod's analog-to-digital (ADC) converter. This digital data is then stored on the microcontroller's processor until it is ready to be transmitted over the BLE connection. The Nordic nRF52832 system on chip (SoC) is built around the processor and includes a transceiver to support communication over BLE.

The software development kit for the Nordic SoC allows the user to implement custom programs for data acquisition and wireless communication. A program was developed that directs the BlueMod microcontroller to regularly one or more of its input pins through an ADC and transmit those digital readings over a BLE connection. In this connection, the BlueMod acts as a peripheral device that is sending data to a central device, the nRF52 DK. The central device is responsible for dictating the terms of a BLE connection. This includes setting the connection interval, which determines how often the central device asks the peripheral device for new data. A shorter connection interval will result in a higher transmission rate because updated values are being sent more often.

To investigate the effects of different transmission rates on the average power consumption of the microcontroller, the connection interval of the BlueMod was varied throughout testing. Bluetooth standards, however, set the lower and upper limit of a BLE connection interval to 7.5 and 4000 milliseconds, respectively. If the hydraulic sensors could only be sampled once every 7.5 milliseconds (or 133 times per second), this would limit the kinds of operating conditions that could be monitored by this sensing node. While BLE transmissions may only occur once every 7.5 milliseconds, no such limit exists for the ADC sampling rate. So, the operating program on the BlueMod has been configured to sample the ADC several times before each BLE transmission and send multiple samples during each connection interval. The current implementation has been configured to sample the ADC 8 times between each transmission and send each of these readings during a single BLE transmission. The structure of this BLE packet is illustrated in Figure 5. When the BLE connection interval is set to 8 milliseconds, this results in an "effective sampling rate" of 1 kHz which would be adequate for high transmission rate sensors like accelerometers or dynamic pressure sensors. The program that acts as the receiver for these transmissions is part of the central base station system and must be updated with the desired connection interval before communication takes place.

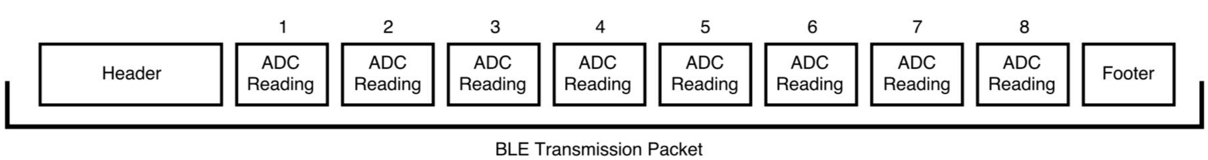

Figure 5: Structure of BLE Transmission Packet

C. Central Base Station

The components of the central base station serve as a receiver for the BLE transmissions sent by the BlueMod microcontroller and locally store the ADC readings from these messages. In an industrial setting, the central base station could be used to give operators information on the operating conditions of a hydraulic system or allow them to manipulate certain parameters of the sensing node such as the rate of transmission or the number of channels being sampled. In the prototype implementation, the central base station is comprised of a Nordic nRF52 Development Board, shown in Figure 6, and a computer.

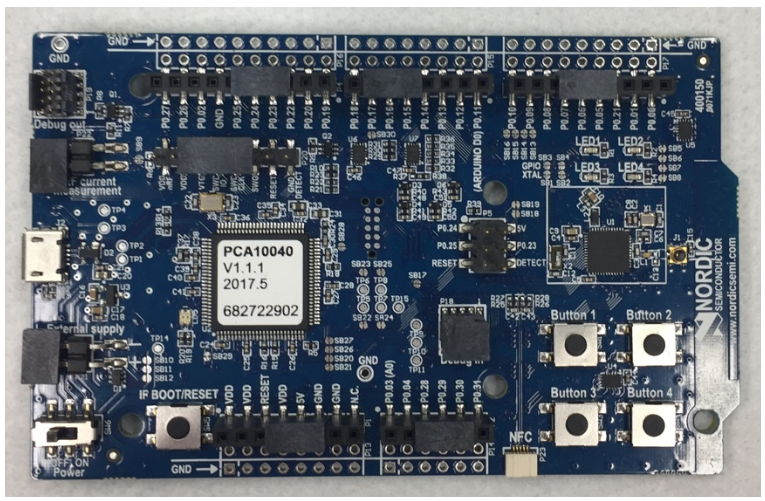

Figure 6: Nordic nRF52 Development Board

This nRF52 board is also running a custom program that allows it to recognize the peripheral BlueMod device and establish a connection with it. The central program running on this device is set up to forward any received BLE transmissions that it receives over a serial connection with a connected computer. During operation, a data collection laptop is running a MATLAB script that establishes a serial connection with the nRF52 device and records any messages sent over this connection. The program then decodes the BLE transmission payload into 8 distinct ADC readings and stores them locally. Upon the receipt of an ADC reading by this laptop, the transmission process for that measurement is complete.

D. Power Consumption Analysis

The levels of energy being harvested from a hydraulic system will dictate how often the BlueMod+S42 microcontroller is able to send transmissions, which will determine the kinds of sensing systems that can be implemented. A sensing system that reports the temperature or static pressure of a hydraulic system may need to send measurements at a rate of about 1 Hz. To monitor the dynamic pressure of the hydraulic fluid or an accelerometer on a piece of machinery with a running hydraulic line, transmission rates on the order of kilohertz will likely be needed. To evaluate the feasibility of using a HPEH device to realize a self-powered hydraulic sensing node, the power consumption of the sensing system described above was measured while operating at varying transmission rates.

The power consumption of the BlueMod was measured while it was sampling ADC readings and sending these values over BLE at various frequencies. The microcontroller was allowed to connect to the central nRF52 device before measurements began and the voltages at two points of the power supply connector were then recorded at a rate of 10 kHz for 10 seconds. The setup for this testing is depicted in Figure 7.

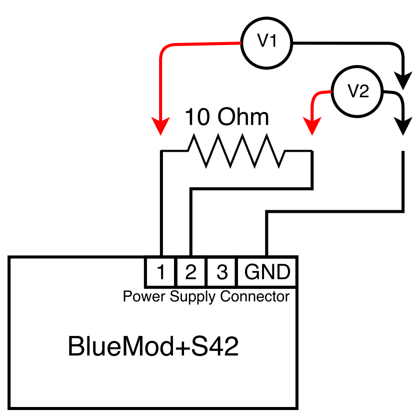

Figure 7: Power Consumption Test Setup

Measurements were performed at several BLE transmission frequencies and each of these transmissions contained 8 ADC readings, causing the sampling rate to be greater than the BLE transmission rate by a factor of 8. These tested frequencies and their effective conversions can be seen in Table 1.

Table 1: Tested BLE Transmission Rates and Effective Sampling Rates

BLE Transmission Rate (Hz)	Sampling Rate (Hz)
1.25	10
2.5	20
12.5	100
25	200
62.5	500
125	1000

At each frequency, the two power supply voltages, V1 and V2, were collected and used to calculate the device's power consumption throughout transmission. This calculation is given below where current coming into the device flows from Pin 1 to Pin 2.

$$\text{Power Consumed} = V_1 \cdot I = V_1 \cdot \left(\frac{V_1 - V_2}{10}\right)$$

CHAPTER 4

RESULTS AND DISCUSSION

By analyzing the relationship between power consumption and transmission rate for this sensing node, it is possible to predict one quantity given the other. This capability is useful for a self-powered sensing system because it allows an operator to predict the transmission rate that could be maintained for a given power generation rate. Additionally, analyzing the power consumed by this system throughout operation has provided insight into how to decrease power consumption in more developed prototypes.

A. Power Consumption at Varying Transmission Rates

A plot of the average power consumption as a function of the sampling rate can be seen in Figure 8. These measurements show a roughly linear relationship between sampling rate and average power consumption. The average power consumptions range from 11 μW to 3.5 mW for tested data transmission rates. This suggests that an energy harvesting device that can produce power on the scale of milliwatts would be able to support transmission rates ranging from 10 Hz to 1000 Hz.

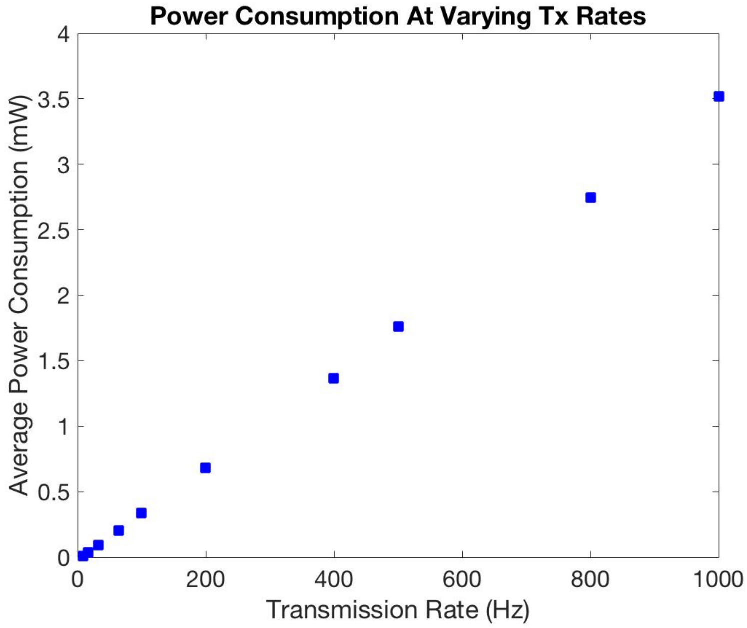

Figure 8: Average Power Consumption of BlueMod at Several Sampling Rates

B. Power Consumption of Different Sensing Processes

Figure 9 depicts the power consumption of the BlueMod microcontroller over one cycle of sampling and transmission. Though this figure shows the power consumption during a single 100 Hz transmission cycle, the pattern depicted here is repeated throughout the connection regardless of transmission rate. The BLE transmission is easily picked out from these graphs as a large spike in power consumption that occurs once per connection interval. The detail view shows that this spike in power consumption is preceded by a smaller peak, possibly due to the microcontroller preparing for transmission. Further inspection shows several smaller peaks in power consumption that correspond to sampling of the ADC. These sampling spikes occur eight times between BLE transmissions and provide the data that is sent over the wireless connection. From these figures it is apparent that the highest power draw for this sensor node prototype occurs during BLE transmissions. The power consumption during these periods peaks at approximately 27.5

mW which is several times larger than the power consumption during ADC sampling, about 6 mW.

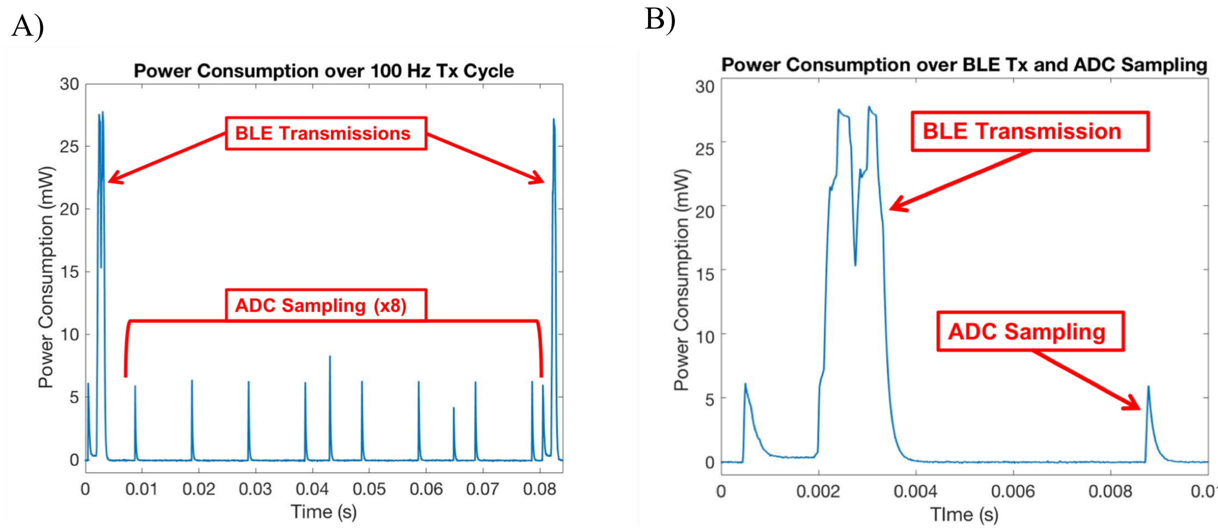

Figure 9: Power Consumed by BlueMod+S42 over (A) one cycle of BLE transmission and (B) one iteration of ADC sampling and subsequent BLE transmission

Integration of the data shown above can be done to quantify the amount of energy that the BlueMod requires for different functions. Over one cycle of ADC sampling and BLE transmission, 39.465 μJ of energy is consumed. If a single ADC sampling event is isolated, integration of this time period shows that 0.85 μJ is consumed. Given that eight sampling events occur during a single transmission cycle, this means that ADC sampling consumes 17.23% of the total cycle energy. The same analysis can be done for a single BLE transmission event. This integration shows that transmission consumes 32.22 μJ, or 81.64% of the total cycle energy. The remaining 1.13% of the energy is consumed while the microcontroller is in standby mode or briefly awakened by to additional timers.

The manufacturer's specifications for the BlueMod+S42 provide a useful point of comparison for these power consumption measurements. The datasheet states that the microcontroller should draw a maximum of 7.5 mA of current during wireless transmission. Given the measured peaks of about 27.5 mW and a supply voltage of 3.2 V (from a connected watch battery), the peak observed current draw is 8.6 mA, slightly higher than the manufacturer specification but still on the same order of magnitude as this value. The low standby power consumption indicates that the BlueMod microcontroller is successfully shutting down all unnecessary processes in between ADC sampling and BLE transmission.

The lowest average power consumption observed during these tests, 11 μW during the 10Hz sampling connection, is several orders of magnitude less than the power harvesting rate of 2.6 mW reported by Schwartz, Skow, and Cunefare [6]. The average power consumption crosses this 2.6 mW threshold between transmission rates of 500 Hz and 800 Hz, indicating that the current HPEH iterations would be able to support a sampling node with transmission rates in this range. Increased power efficiency may be achieved by altering the operation of the BlueMod's ADC. The current program involves starting and stopping the ADC each time a sample needs to be read but a more efficient implementation would place the ADC into standby mode between measurements. Further improvements may be possible by sampling the ADC more than eight times between wireless transmissions.

CHAPTER 5

CONCLUSION

A proof-of-concept, self-powered sensing device has been designed and built. This system includes a piezoelectric energy harvesting device to produce consistent power from a hydraulic system, a power conditioning and storage subsystem, and a microcontroller to sample sensor measurements and transmit them over a wireless connection. As sampling and transmission rates increase, power consumption by this system has been shown to increase. Average power consumption ranges from 11 μW to 3.5 mW for 10 Hz to 1,000 Hz transmission rates, respectively. This experimental relationship between power consumption and transmission rate may serve as a useful reference for system operators seeking to implement a self-powered sensing system. The majority of power is consumed during wireless transmission over a BLE connection which requires significantly more power than sampling analog sensors. This power requirement is feasible for current iterations of HPEH devices and further work will be focused on reducing the energy consumption of the sensor node by manipulating the operation of the BlueMod's ADC and modifying the sampling and transmission schedule. Decreasing the required power even further may allow a single hydraulic energy harvester to power a network of sensors distributed throughout a hydraulic system.

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